An Aircraft Lifecycle Approach for the Cost-Benefit Analysis of Prognostics and Condition-based Maintenance based on Discrete-Event Simulation

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ABSTRACT

The paper will provide a lifecycle cost-benefit analysis of the use of Prognostics and Health Management (PHM) systems and a conditioned-based maintenance (CBM) concept in future aircraft. The proposed methodology is based on a discrete-event simulation for aircraft operation and maintenance and uses an optimization algorithm for the planning and scheduling of CBM tasks. In the study, a 150-seat short-range aircraft equipped with PHM and subject to a CBM program will be analyzed. The PHM-aircraft will be compared with an Airbus A320-type of aircraft with maintenance expenditures equivalent to a conventional block check maintenance program. The analysis results will support the derivation of technical and economic requirements for prognostic systems and CBM planning concepts.

1. INTRODUCTION

Aircraft operators are under pressure to increase aircraft availability and operability in the future and continue to reduce the cost of aircraft operation. Reductions of maintenance downtimes and expenditures and the prevention of operational interruptions can help to achieve these objectives.

Technical and aircraft equipment was the most occurring direct delay category in 2006, with 10.2 % of total delays (Eurocontrol, 2007). When aiming for significantly higher reliabilities of future aircraft, it should be considered that 20 % to 50 % of all unscheduled removals are no-fault-founds (NFF) (Söderholm, 2007).

Prognostic concepts can positively influence the areas safety, maintainability, logistics, lifecycle costs, system design and analysis, and reliability of a product (Sun et al., 2010). There is a large potential for the reduction of overall life cycle costs of an aircraft by implementing comprehensive diagnostic and prognostic concepts (Roemer et al., 2001; Keller and Poblete, 2011; Scanff et al., 2007).

PHM may help to reduce operational interruptions due to unscheduled maintenance events, and maintenance downtimes due to (unnecessary) preventive maintenance. While significant advances in PHM systems are announced by industrial and academic research, several challenges have to be resolved for the onboard deployment of an aircraft-wide system (Sun et al., 2010). Besides the solving of technical issues one important prerequisite of an implementation is the provision of a reliable cost-benefit assessment of the onboard use of PHM. Such an analysis must be able to capture all relevant impacts of the technology on aircraft operation and maintenance over the aircraft lifecycle.

It has to be differentiated between general impacts, which can be also achieved through an installation of (retrofit) PHM systems in legacy aircraft, and wider impacts, which require extensive certification effort and/or the implementation of PHM during an early aircraft design stage.

In general, prognostic systems provide early detection of the precursor (and/or incipient) fault condition of a component and are capable to predict its remaining useful life (RUL) (Engel et al., 2000). In addition, the fault isolation and identification capabilities of PHM contribute to a reduction of no-fault-founds (NFFs) and support the trouble shooting process (Leao et al., 2007).

Further benefits require consideration of PHM in the certification phase or already in the aircraft design phase. Significant reductions in maintenance downtimes and costs can only be realized when a paradigm shift from periodic, preventive maintenance towards a predictive (i.e. condition-based) maintenance strategy takes place. The major

expected benefits in this case are substitutions of preventive inspection tasks and reductions of waste of (component-) lives. This leads to reductions of overall maintenance cost and downtimes. These effects additionally influence spare parts pooling due to reduced spare parts demand and thereby allows a reduction in capital commitment (Hölzel et al., 2012).

Today´s maintenance programs are characterized by periodic, preventive and corrective tasks. While periodic tasks are foreseeable and easy to plan, time and effort for corrective work is more difficult to plan as they arise from the results of (preventive) inspections. With prognostics, many preventive inspections may become obsolete, while predictive tasks have to be planned and carried out with (potentially) short warning times. The increased planning complexity requires a different maintenance planning approach in order to achieve the aimed goals of a PHM and CBM implementation. Furthermore, CBM may lead to increasingly fluctuating demands for spare parts and new requirements to the maintenance supply chain.

The benefits, which can be realized in a specific application, depend on the current maintenance concept and the criticality of the monitored item in terms of safety and operational reliability of the aircraft. Therefore, a detailed modeling and analysis of all relevant factors and economic conditions is required.

2. GOAL OF STUDY

In general terms, this paper aims to facilitate informed decision making through the analysis and evaluation of PHM systems and CBM concepts in future aircraft. More specifically, it is the goal of this study to propose an appropriate method for analyzing the economic potentials of a PHM implementation in future aircraft in combination with a CBM planning concept. The applied methodology should be generic and feasible to analyze existing and future aircraft.

An approach is needed, that considers all phases in aircraft lifecycle and includes all relevant impacts of PHM systems and existing interdependencies with other elements of the air transportation system in a comprehensive way. In particular the selected approach has to consider the influence of a PHM use on aircraft operation. The use of a discounted cash-flow method is required to take into account the time value of money when assessing an aircraft over its entire lifecycle.

To consider uncertainties in component failure behavior, the methodology used in the study should be based on individual component failure probability functions. Performance levels (i.e. false alarm rates and missed failure rates) of PHM systems have to be included to account for imperfect sensors or prognostic algorithms. Previous analyses have shown that the prognostics performance level has a significant impact on the added value of a PHM system (Hölzel et al., 2012).

Furthermore, the selected approach should be able to model the operational and economic impacts of a CBM strategy. It should cover scheduled and unscheduled maintenance.

The approach is demonstrated in a case study to show the potential economic benefits of a PHM/CBM concept from an airline perspective.

3. METHODOLOGY

Economic assessments of PHM applications have been discussed by many authors (e.g. Banks et al., 2005; Feldman et al., 2009; Leao et al., 2007; Sandborn & Wilkinson, 2007; Scanff et al., 2007). Typical measures are lifecycle costs (LCC) or return-on-investment (ROI) estimates of the implementation costs and the potentials for cost avoidance (e.g. Banks et al., 2005). Leao et al. (2007) developed a cost-benefit analysis (CBA) methodology for PHM applied to (legacy) commercial aircraft. The method comprises a comprehensive set of equations for the quantification of benefits and costs, which are related to a PHM implementation. Their approach is capable to conduct assessments from an aircraft manufacturer's or operator's perspective, but it requires many inputs from technical analyses and PHM specialists. Sandborn and Wilkinson (2007) have proposed a lifecycle cost approach including a maintenance planning model based on discrete-event simulation. They consider various uncertainties with regard to PHM systems by using probability distributions as inputs for the model. The model provides a detailed picture of the usefulness of PHM on component or sub-system level, while it does not cover additional impacts and interactions on overall system (i.e. aircraft) level.

Both levels of analysis, component and overall system level, are needed, when a profound CBA of PHM with particular attention on the implementation of CBM should be provided. As outlined in section 2 the cost-benefit model must cover the relevant impacts of PHM on component or sub-system level and should consider the corresponding uncertainties. This component level must then be integrated on aircraft level, in order to simulate the effects of PHM and CBM in a realistic aircraft operation scenario.

The assessment approach presented in the paper is based on a discrete-event simulation of aircraft operation including a branch-and-bound algorithm for maintenance planning optimization. A lifecycle cost-benefit model evaluates the simulation results using a discounted cash-flow method. The presented simulation and assessment tool is modeled in MATLAB©. Aircraft type and operator specific XML-files are used to configure and control the lifecycle analyses.

3.1. Aircraft Lifecycle Approach

New technologies or concepts for the air transportation system need not only to lead to technological improvements, but also have to show economic advantages compared to the current system.

Direct operating cost (DOC) is an established metric to perform economic valuation of existing aircraft or future aircraft concepts. DOC formulae use global technical, operational, and economic parameters to come up with an average DOC value on a flight-cycle or flight-hour basis.

When assessing technologies and processes with impacts on the air transportation system level, all phases of the life cycle and interdependencies with other system elements have to be considered. New maintenance concepts influence maintenance cost and aircraft availability. To capture time and cost aspects, the lifecycle cost-benefit model AIRTOBS (Aircraft Technology and Operations Benchmark System) was developed.

The model is generic in nature and is feasible for economic assessments of various aircraft technologies and operation concepts from an operator's perspective. Apart from the assessment of prognostic concepts (Hölzel et al., 2012), studies on aircraft with natural laminar flow (Wicke et al., 2012) or intermediate stop operation concepts (Langhans et al., 2010) have been conducted.

It models all economic relevant parameters along the aircraft life cycle. The aircraft operational lifecycle is initiated by the acquisition of an aircraft and ends with the decommissioning. The model includes aircraft specific parameters (e.g. acquisition cost, fuel consumption, seating capacity, crew size, and aircraft specific charges), operational aspects (e.g. route network, maintenance concepts and costs, and ticket prices), as well as global boundary conditions (e.g. fuel price trend, annual inflation rate). AIRTOBS focuses on the perspective of an aircraft operator and includes methods to account for costs and revenues.

An overview of AIRTOBS is shown in Figure 1. It consists of three main modules. The Flight Schedule Builder (FSB) generates a generic aircraft lifecycle flight schedule based on airline route data assuming full aircraft availability (i.e. no maintenance). Routes are considered based on the aircraft cycle time including flight time, taxi and runway operation times, and turnaround time.

This provisional flight schedule serves as the fundament for the Maintenance Schedule Builder (MSB). The MSB executes a simulation run of the flight operation and maintenance events over the aircraft lifecycle. The MSB uses input data from maintenance databases for the modeling of scheduled and unscheduled maintenance events, including airframe, engine and component maintenance.

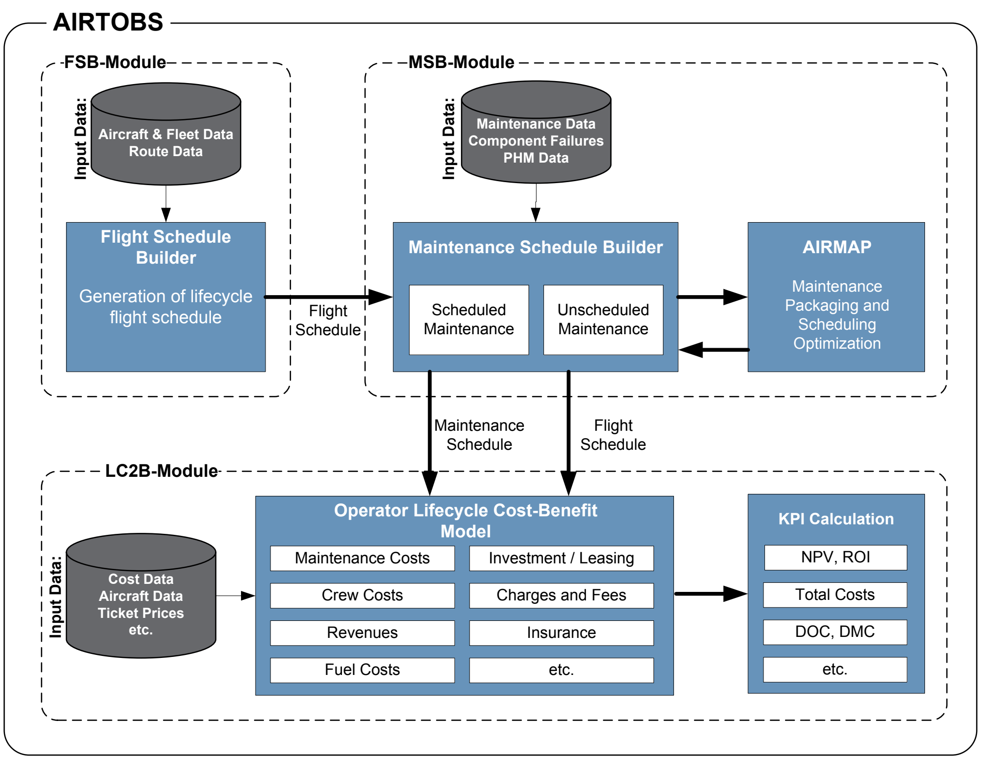


Figure 1. Lifecycle cost-benefit model.

To analyze an application of PHM in combination with a CBM planning concept, a task-oriented maintenance modeling is used for the corresponding maintenance

activities. A maintenance packaging and scheduling optimization (AIRMAP) module (outlined in section 3.3) allocates maintenance tasks to maintenance events in a way that minimizes overall maintenance cost while ensuring that all scheduled flights can be carried out.

After the optimized maintenance schedule and the adjusted flight schedule are generated, the results are passed on to the Operator Lifecycle Cost-Benefit Model (LC2B), where costs and revenues are calculated. The actual time of occurrence of the cost and revenue elements is captured to account for the time value of money. All values are escalated over the aircraft lifecycle to account for inflation, before they can be summarized as net present value (NPV). It can be calculated as given in Eq. (1), where C_0 is the initial investment (i.e. aircraft price) and C_i is the cash-flow in the i-th year. The discount rate r represents the rate of return that could be achieved with equivalent investment alternatives in the capital market (Brealey, Myers, & Franklin, 2006). In business practice, a company or industry weighted average cost of capital (WACC) is often used as discount rate.

$$NPV = -C_0 + \sum_{i} \frac{C_i}{(1+r)^i} \tag{1}$$

The NPV is one among many other metrics that are calculated in AIRTOBS and can be used for the comparative evaluation of aircraft technologies and (operational) concepts.

3.2. Modeling of Maintenance Events and PHM Impacts

This section describes the modeling of maintenance events and the logic how the impacts of PHM on scheduled and unscheduled maintenance is implemented in the MSB module as depicted in Figure 1. The maintenance modeling is realized as discrete-event simulation based on the scheduled flights in aircraft lifecycle.

3.2.1. Scheduled Maintenance

Scheduled maintenance is considered depending on discrete, interval-based events. Intervals are specified by flight hours (FH), flight cycles (FC), and calendar time (years, months, days). Each event has a specific ground time, during which the flight schedule is adjusted while producing time discrete costs to the airline. To account for operating experience and maturity effects in maintenance, maturity curves are provided within the model. The maintenance schedule created by the MSB follows (by default) a traditional block check concept for line and base maintenance.

3.2.2. Unscheduled Maintenance

In order to model unscheduled maintenance, one must have knowledge of the failure behavior of the respective components or systems. This is achieved by using non-parametric failure distribution functions, which have been calculated on the basis of historic maintenance data. Particularly in order to attain feasible computing times in the following simulation process and to guarantee an appropriate size of the random sample, one distribution function was calculated for any component within ATA Chapters with identical first three digits (ATA 3D Chapter, i.e. subsystem level) (Hölzel et al., 2012).

Using the previously created lifetime flight schedule, unscheduled events are simulated based on component failure behavior, aircraft related mean times to repair (MTTR) and maintenance man-hours, e.g. downtime and man-hours needed for replacement of a component or LRU. In detail, the MSB module uses component lifetimes randomly drawn from previously described failure distribution functions. NFF events are modeled based on the NFF probabilities per FH that have been calculated from in-service data. The occurrence of an NFF event leads to an unscheduled removal of a component. PHM false alarm events are modeled in the same way as NFFs (Hölzel et al., 2012).

Component failures produce costs for labor and material. Furthermore they can result in flight delays or cancellations depending on the minimum equipment list (MEL), the MTTR, and the planned aircraft turnaround time. Delays are modeled as a reduction in aircraft availability and a cost element that covers passenger compensations and accommodation. Unscheduled failures not meeting the MEL-conditions can cause a flight cancellation when the remaining availability is not adequate to execute all planned flights of the respective day. In addition, a certain delay time threshold can be defined, which enforces a cancellation when a delay exceeds the threshold.

To consider the influences of maintenance strategies and component reliabilities on spare parts provisioning, related inventory costs are modeled. Overall LRU inventory costs are modeled based on estimated component quantities to meet a desired service level and the total carrying cost (capital and inventory cost). The estimated component quantities are calculated based on the aircraft utilization, quantities per aircraft, mean times between unscheduled removals (MTBURs), repair turnaround times and fleet size (Khan et al., 1999).

3.2.3. Impacts of PHM

An implementation of prognostics in aircraft systems can lead to a variety of operational and economic benefits. The main capability of PHM is the provision of advanced warnings of failures. The following benefits deriving from this capability are in focus of this study:

1. Reduction of unscheduled events due to failures (and NFFs) of items/components.

2. Enabling CBM: Transition from preventive to condition-based maintenance measures.

The underlying effects of PHM on aircraft maintenance are modeled in different ways.

The impact of PHM on unscheduled events is modeled in the unscheduled maintenance module as described in section 3.2.2. Impending failures or NFFs that are successfully detected by the prognostic system no longer result in unscheduled events. While NFF events are assumed to be completely avoided by PHM impending failures result in CBM tasks. Those CBM tasks are subject to the maintenance planning process described in the following section 3.3. Since no diagnostic or prognostic system will operate completely perfect, it is necessary to consider possible prognostic failures in the model. Two types of prognostic failures are taken into account:

1. False alarm: Prognostic system detects an impending failure, although no failure is impending, or system reports impending failure early.
2. Missed failure: Prognostic system does not detect an impending failure or detects it late.

Each failure of an item that is initially covered by PHM can evolve into a missed failure with a certain probability. A missed failure event has the same consequences as a failure not covered by PHM. The probabilities of false alarm and missed failure events depend on the performance level of the PHM system and are input values of the model.

The potential impact of PHM on preventive, scheduled maintenance tasks depends on its task-code. Scheduled maintenance tasks can be assigned to a variety of different task codes (Airbus, 2007) as listed in Table 1. While tasks with some task codes could become redundant if a PHM system is used, prognostics have no influence on other scheduled tasks listed in the scheduled maintenance program (MPD).

For the sake of simplification and generalization, the task codes are summarized to six task code groups (TCG) within the model as shown in Table 2. TCG 1 to 3 reflect tasks, which are potentially redundant, if a PHM system covers the contained tasks. The model assumes that the prognostic system is able to automatically carry out a certain fraction of the check- or inspection-tasks in a continuous or non-continuous manner. The fraction of tasks covered by a PHM system can be adjusted with the task redundancy parameter P_{TR}. It is obvious that this parameter is depending on the overall PHM coverage rate, but it is not necessarily identical. The parameter P_{TR} implies that it is possible to eliminate the corresponding scheduled maintenance task from the MPD under consideration of certification requirements.

Table 1. Maintenance task codes.

Task Code	Definition
BSI	Borescope inspection
CHK	Check for condition, leaks, circuit continuity, check fluid reserve on item, check tension and pointer, check fluid level, check detector, check charge pressure, leak check/test.
DI	Detailed inspection
DS	Discard
FC	Functional check/test
GVI	General visual inspection
LU	Lubrication
OP	Operational check/test
RS	Remove for restoration
SDI	Special detailed inspection
SV	Drain, servicing, replenishment (fluid change)
TPS	Temporary protection system
VC	Visual check

Table 2. Task code groups and potential PHM impact.

Task code Group (TCG)	Included task codes	Potential impact of PHM
TCG 1	CHK, OP, FC	Task elimination
TCG 2	GVI	Task elimination
TCG 3	DI, SDI	Task elimination
TCG 4	SV, DS, RS	Interval escalation
TCG 5	Non-routine	Interval escalation
TCG 0	Non-routine / other	No impact

If a significant fraction of scheduled tasks can be eliminated through a PHM implementation, this reduces the total workload and potentially also the aircraft downtime of a maintenance check. Without special consideration of the minimum duration of certain tasks (“shortest path”), the influence of PHM on aircraft downtimes can be estimated as shown in Eq. (2).

$$t_{DT,new} = t_{DT,0}\left(1 - P_{TR} \cdot r_{routine} \cdot r_{TR}\right) \tag{2}$$

$t_{DT,new}$ resulting maintenance downtime

$t_{DT,0}$ maintenance downtime without PHM impact (reference case)

P_{TR} task redundancy parameter

r_{TR} ratio of routine tasks potentially redundant in case of PHM use

$r_{routine}$ ratio of routine task man-hours to complete man-hours of check

It is assumed that preventive maintenance tasks related to TCG 4 have to be carried out less frequently when the corresponding items are monitored by PHM. This means, the former limited service life of the item is extended

through the use of PHM depending on the actual condition. Since no component degradation models are available for this study, the influence of PHM on service life is modeled with the interval escalation parameter P_{IE}, which is assumed as input value and can be varied in a parameter variation.

In addition to routine activities, scheduled checks also comprise large amounts of non-routine tasks. Detected findings result in non-routine activities (i.e. repairs or replacements of the respective items), when the degradation may reach a critical state prior to the next preventive inspection. It is assumed that a certain part of these non-routine tasks can be conducted at a later time, the respective items are subject to a CBM strategy (and monitored by PHM). These tasks are summarized in TCG 5. The last task code group (TCG 0) includes non-routine (e.g. findings that are critical for flight safety and thus have to be repaired immediately) and other tasks (e.g. cabin refurbishments and paintings) to which a PHM system has no influence.

3.3. Condition-based Maintenance Planning

The planning of aircraft maintenance is the allocation of maintenance tasks (i.e. objects) that must be carried out on specific aircraft to maintenance capacities (i.e. bins). Combinatorial problems of this character are of higher complexity and are very similar to the elementary bin-packing problem (Fukunaga et al., 2007; Bohlin, 2010). Since the aircraft maintenance planning, as discussed in this paper, considers more variables and constraints as the "simple" bin packing problem, it is very likely to be NP-hard [1]. Although the problem might not be solved in polynomial time, solutions can efficiently be verified, e.g. by using a branch-and-bound algorithm (Korte et al., 2006; Schröder, 2011).

In this study, each ground time of an aircraft (turnaround times and overnight stays) is regarded as a maintenance opportunity. It is the goal to minimize aircraft maintenance costs and to utilize existing maintenance opportunities efficiently while aircraft rotation planning and limited maintenance capacities are considered. This is achieved by appropriate grouping of maintenance tasks, while considering technical (maintenance intervals or RULs determined by a PHM system) and organizational restrictions. The process of grouping of tasks is referred to as maintenance task packaging in the following. The packaging of tasks allows an efficient use of maintenance opportunities but leads to waste of life when items are maintained earlier than required or tasks are performed before due date. The cost of wasted life is calculated as described in Eq. (3).

[1] NP-hard describes a class of problems in computational complexity theory.

$$c_i^w = \frac{t_i^{life} - t_i^{RUL}}{t_i^{life}} \cdot c_i^{task} \tag{3}$$

c_i^w	cost for wasted life of task i
c_i^{task}	cost for performing task i (labor, material, logistics)
t_i^{life}	complete life or interval of task i
t_i^{RUL}	RUL or remaining time until due date of task i at time of task execution

The maintenance planning problem can be formulated with the objective function and the related constraints described in Eqs. (4) to (16).

$$\min \sum_{i \in I} \left(c_i^{task} + c_i^w\right) + \sum_{j \in J} c_j^{opp} + \sum_{k \in K} c_k^{fixed} \tag{4}$$

$$\sum_{i \in I} d_i x_i^k \leq m_k \qquad \forall k \in K \tag{5}$$

$$\sum_{i \in I} \sum_{p \in P} x_i^k y_i^p \leq s_k \qquad \forall k \in K \tag{6}$$

$$\sum_{i \in I} \sum_{j \in J} l_j^k x_i^k z_i^j = l_k \qquad \forall k \in K \tag{7}$$

$$\sum_{i \in I} x_i^k q_i = q_{s,k} \qquad \forall k \in K, \forall sk \in Q_k \tag{8}$$

$$\begin{aligned}&\max\left(u \cdot t_i^{max}, t_i^{last} + u \cdot t_i^{max,int}\right)\\ &\leq t_i \leq \max\left(t_i^{max}, t_i^{last} + t_i^{max,int}\right)\end{aligned} \qquad \forall i \in I \tag{9}$$

$$t_k \leq t_i \qquad \forall i \in I, \forall k \in K \tag{10}$$

$$t_j^{min} \leq t_i \leq t_j^{max} \qquad \forall i \in I, \forall j \in J \tag{11}$$

$$d_i^{MTTR} \leq t_j^{max} - t_j^{min} \qquad \forall i \in I, \forall j \in J \tag{12}$$

$$\begin{aligned}&t_i^{last} + t_i^{max,int} - t_{end}\\ &\leq t_{tranfer} \wedge t_i^{max} - t_{end} \leq t_{transfer}\end{aligned} \qquad \forall i \in I \tag{13}$$

$$x_i^k \in \{0,1\} \qquad \forall i \in I, \forall k \in K \tag{14}$$

$$y_i^P \in \{0,1\} \qquad \forall i \in I, \forall p \in P \tag{15}$$

$$z_i^J \in \{0,1\} \qquad \forall i \in I, \forall j \in J \tag{16}$$

Definition of symbols:

i	index for maintenance task to be performed
I	set of maintenance tasks to be performed
j	index for maintenance opportunity
J	set of maintenance opportunities
k	index for maintenance location
K	set of maintenance locations

p	index for aircraft (tail-sign)
P	set of aircraft
Q_k	set of capabilities at maintenance location k
d_i	man-hours required for task i
d_i^{MTTR}	mean time to repair for task i
q_i	aircraft type of task i
t_i	actual starting time of execution of task i
t_i^{max}	RUL or remaining time until due date of task i
u	minimum usage factor for all t_i^{max} ($0 \leq u \leq 1$)
c_j^{opp}	fixed cost for usage of maintenance opportunity j
l_j	place of maintenance opportunity j
t_j^{min}	beginning of maintenance opportunity j (arrival of aircraft)
t_j^{max}	end of maintenance opportunity j (departure of aircraft)
$t_i^{max,int}$	maximum time between two events of task i
t_i^{last}	date of last allocation of task i
t_{end}	end of period
$t_{transfer}$	length of time from which a task is transferred to the next planning period
c_k^{fixed}	fixed cost for usage of maintenance location k
l_k	place of maintenance location k
m_k	available man-hours at maintenance location k
$q_{s,k}$	capability s at maintenance location k
s_k	available maintenance slots at maintenance location k
t_k	earliest availability of maintenance location k
x_i^k	1, if i is performed at k; 0, otherwise
y_i^p	1, if i belongs to p; 0, otherwise
z_i^j	1, if i is performed at j; 0, otherwise

The objective function of the maintenance planning problem is depicted in Eq. (4). The sum of all costs for the execution of maintenance tasks within the current planning period should be minimized. Equations (5) to (16) comprise the constraints, which are considered for this study. Equation (5) limits the total man-hours that can be allocated at a maintenance location. The slot restriction in Eq. (6) defines that the number of aircraft allocated to a maintenance location must not exceed its number of available maintenance slots. Equation (7) ensures that place of the maintenance opportunity l_j is identical with the maintenance location l_k. The maintenance location k has to be capable (i.e. has to be certified and must have the necessary equipment) to perform task i (Eq. (8)). Equation (9) describes that the time of execution t_i of task i must not be later than t_i^{max} and not before the minimum lifetime utilization ut_i^{max}. In the case of a multiple assignment of the same task within one period, the execution time of the task must refer to the respective task. The location availability constraint Eq. (10) describes that the time of availability t_k of location k must not be later than the time of execution t_i of task i. Equation (11) defines that the execution of task i must take place during a ground time of the aircraft. The ground time of the aircraft must be at least as long as the MTTR of the longest task to be allocated (Eq. (12)). The constraint Eq. (13) ensures that a task is allocated in the current period if its remaining time t_i^{max} exceeds the end of the period by no more than the buffer time $t_{transfer}$. Equations (14) to (16) are binary decision variables that allocate a task i to a location k, an opportunity j, and an aircraft p.

The CBM planning function used for this study is implemented in the AIRMAP model, which is a sub module of AIRTOBS (as shown in Figure 1). AIRMAP uses an optimization approach that can be characterized as depth-first-search branch-and-bound algorithm. The resulting task packaging and maintenance scheduling process is illustrated in Figure 2. The figure shows due dates (marked with an "X") for a number of tasks ("Task 1" to "Task n") in two random periods in aircraft life. For each planning period, the algorithm searches for a cost-minimal maintenance plan in an iterative process. The resulting maintenance events are marked with vertical dotted lines. The distances between the time of an event and the due dates of the allocated tasks represent the waste of life (expressed in FH). Due to the limitation of maintenance capacities and individual costs and man-hours of the tasks, it can be feasible to allocate a task to an event other than the nearest (e.g. allocation of second due date of "Task 5" to "Event 2" in Figure 2).

It is possible that the optimizer cannot allocate tasks, which are due shortly after the beginning of a new period because of a lack of maintenance opportunities. To avoid this, the user of the optimizer can define a buffer period that forces the algorithm to allocate the respective tasks in the preceding period (e.g. the third execution of "Task 1" is allocated to "Event 3" in Figure 2).

In this study, preventive scheduled and condition-based maintenance activities are subject to the previously described maintenance planning optimization. The maintenance optimization is designed as a dynamic planning approach that responds to varying maintenance needs and airline operation during aircraft lifecycle. This is achieved by splitting the operating lifecycle into shorter planning periods (e.g. four weeks) that are run through sequentially. This approach seems to be more realistic compared to a single optimization covering the complete lifecycle. In addition, this procedure leads to a significantly reduced computation time due to the reduction of the optimization

problem. In theory, longer planning periods would lead to better solutions from a lifecycle perspective.

The optimizer plans maintenance events for planning periods sequentially (beginning with aircraft entry into service). The algorithm takes into account only those tasks that are due in the current planning period. All other tasks are moved to the next planning period.

- a (lifecycle) flight schedule,
- economic boundary conditions like fuel price, ticket prices, labor cost, etc.

Based on the specified PHM system and a selected aircraft the component failure analysis is performed. This analysis results in unscheduled events and failures covered by PHM, which occur in the operating lifecycle. In parallel, the

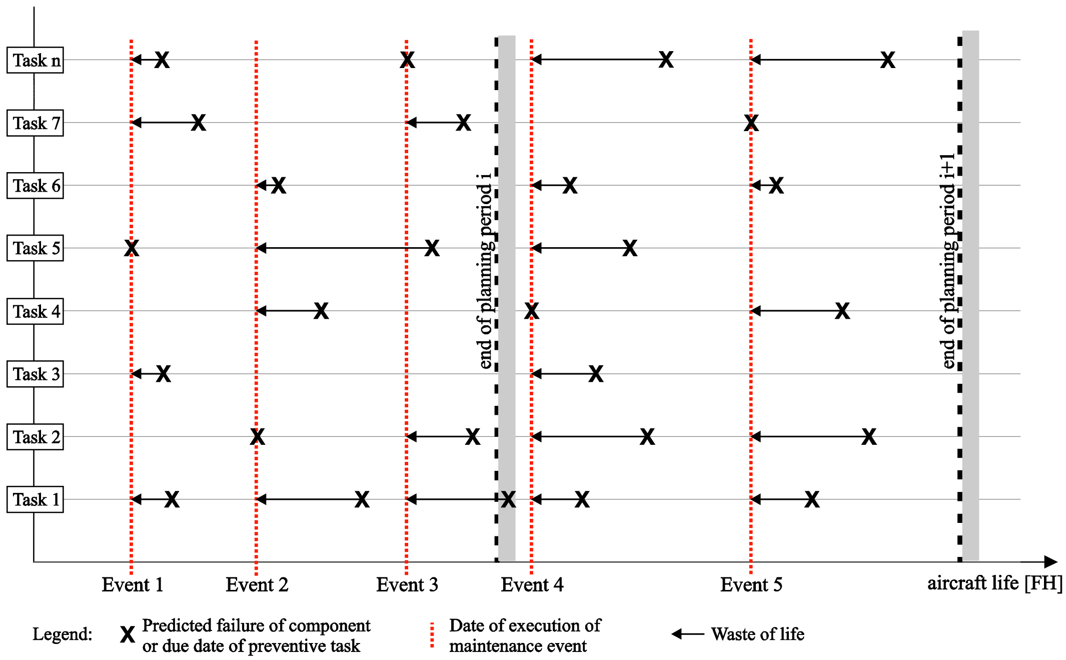


Figure 2. Maintenance scheduling and task packaging.

AIRMAP submits the best plan found to the Maintenance Schedule Builder (as depicted in Figure 1), which then generates the overall lifecycle maintenance and flight schedule as basis for the economic assessment in the LC2B module.

3.4. Assessment Approach

In the study, a 150-seat short-range aircraft equipped with PHM and subject to a CBM program will be analyzed and compared with the baseline. The baseline is formed by an Airbus A320-type of aircraft and a maintenance program equivalent to real world maintenance efforts in terms of man-hours (MH) and cost.

The economic analysis will follow the assessment approach as outlined in Figure 3. Required input data for the analysis are:

- the PHM concept to be analyzed, with specification of covered subsystems or components, corresponding prognostic performance levels and costs,
- a reference aircraft with its scheduled maintenance program, component failure behavior, DOC, etc.,

scheduled maintenance program is analyzed in terms of cost and man-hours efforts per task code. On this basis, a simplified maintenance program for the following analysis steps is modeled.

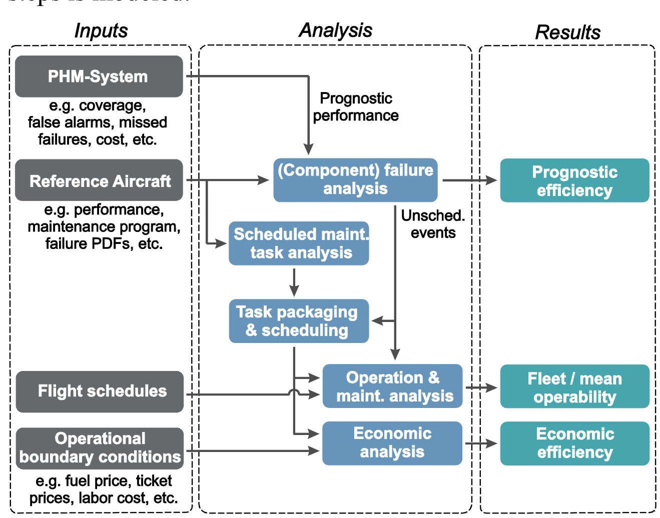


Figure 3. Assessment approach.

The maintenance scheduling and task packaging function then uses the results from both preceding steps und produces the optimized maintenance plan.

After that the analysis of aircraft operation and maintenance as well as the economic assessment are conducted using the AIRTOBS model.

Parametric studies will show the influences of prognostic performance levels, CBM implementation and maintenance planning constraints. From these studies, it is possible to derive essential requirements for prognostic systems and CBM concepts, e.g. minimum performance levels, maximal costs for acquisition and operation and minimum maintenance capacities, under given conditions.

4. ANALYSIS

The following analysis is intended to demonstrate that the proposed analysis approach is suitable to assess the overall benefits and costs of the use of PHM and CBM planning in aircraft lifecycle. While the results provide no answers regarding the suitability of specific PHM approaches or system architectures, they make it possible to derive technical and economic requirements for those in a subsequent step.

Studies following the proposed assessment approach require extensive data, which is usually – at least partially – considered confidential by airlines and maintenance, repair & overhaul (MRO) companies. For this reason, the authors have preferably used publicly available information only or have derived the required data under use of assumption from this information. The following section describes the essential data and the assumptions made for this study.

4.1. Data and Assumptions

An aircraft similar to an Airbus A320 will be used as a reference in this study. This applies to the typical aircraft operation, the maintenance program and all recurring and non-recurring costs as well as expected revenues in the operational lifecycle of this type of aircraft.

It is assumed that aircraft configurations used in this study have the same technology level as today's A320 aircraft, but with PHM installed.

The following sections describe the data and assumptions made for the aircraft operation, scheduled and unscheduled maintenance, and relevant operational boundary conditions.

4.1.1. Aircraft Lifecycle and Operations

An operating lifecycle of 25 years is assumed in this study. The aircraft is operated by a full-service network carrier on a short-range rotation with a daily utilization of 7.5 FH. Table 3 shows details of an assumed aircraft operation.

Table 3. Aircraft operational data.

Parameter	Unit	Value
Operating days/week	[d]	7
Night curfew	[h]	7
Flights per day	[FC]	6
FH/FC	-	1.25
Taxi time per FC	[h]	0.3
Turn-around time	[h]	0.75
Block fuel	[kg]	4,000

4.1.2. Scheduled Maintenance

The major part of the scheduled maintenance requirements for an aircraft is defined in the MPD. This manufacturer documentation contains maintenance tasks with specification of intervals and required man-hours that are to be carried out during service life. Maintenance cost data and more realistic estimates of the related man-hours are for example published by Aircraft Commerce (2006). These data describe traditional block check concepts as still followed by many aircraft operators today.

The intended transition from preventive to condition-based tasks in this study, however, requires an equalized or task-based approach. To enable a convincing CBA of PHM and CBM, it must not be mixed with a comparison between block check and equalized or task-based maintenance concepts.

This leads to the necessity that also the reference maintenance program needs to follow a task-based approach.

Table 4. Scheduled maintenance program A320 (derived from Aircraft Commerce, 2006).

Check	Down-time [h]	Interval	MH [h]	Material cost [US$]
Transit & Pre-flight	0	1 FC	2.6	7
Ramp Check	0	2 d	4	500
Service Check	0	7 d	10	700
A-Check	24	600 FH	80	5.5 k
C-Check	138	18 mo.	2,000	38 k
IL-Check	336	72 mo.	14,300	380 k
D-Check	672	144 mo.	20,000	1.5 M

Following this approach, a simplified task-based maintenance program has been modeled, which is equivalent to the real A320 maintenance program in terms of man-hours and cost as described in Table 4. The maintenance events outlined in Table 4 cover routine and non-routine tasks as well as cabin refurbishments and

typical volume of work resulting from Airworthiness Directives (AD) and Service Bulletins (SB).

The modeled reference maintenance program, referred to as equivalence maintenance program in the following, consists of two parts:

1. Task-based concept for short and medium interval tasks (former Service Check, A-Check, and C-Check),
2. Block checks for long interval tasks (former IL- and D-Check).

Transit & Pre-flight Checks can be performed at any airport and do not require an additional maintenance downtime. That is why these checks are not considered for the composition of an equivalence maintenance program and in the following maintenance planning and optimization process.

Analyses of the scheduled maintenance tasks contained in the A320 MPD result in the shares of the different task codes (as previously described in Table 1) shown in Figure 4. The derived man-hours shares have been clustered according to their interval lengths. For this purpose, a pragmatic division into short, medium and long intervals has been made. While the short and medium intervals correspond to the intervals of the former Service, A-, and C-Checks, the long intervals comply with the IL- and D-Check intervals. These values form the basis for the modeled routine tasks of the equivalence maintenance program.

While the MPD only consists of routine maintenance tasks, non-routine tasks account for a large part of overall maintenance expenditures. It is assumed for this study that there are non-routine tasks that could be performed at a later time, if a PHM (or structural health monitoring) system monitors the health state of the respective item (e.g. cracks in a structural component, which are not critical at the time of discovery).

However, there are non-routine and other maintenance tasks, which are not influenced by PHM at all (e.g. repairs or removals of faulty items, cabin overhauls, painting, or tasks resulting from ADs or SBs). Since no detailed breakdown of non-routine workload could be determined, the ratio of TCG-5 to TCG-0 is assumed as 50:50 in the following.

The allocation of short and medium interval man-hours to their respective TCGs results in the first part of the equivalence maintenance program shown in Table 5.

The modeled equivalence maintenance program consists of 12 short interval and 71 medium interval tasks, which represent the maintenance man-hours and task code groups shown in Table 5 over the lifecycle of 25 years. The short interval tasks are characterized by intervals between 80 and 1000 FH. The intervals of the medium interval tasks range from 4,500 to 13,500 FH.

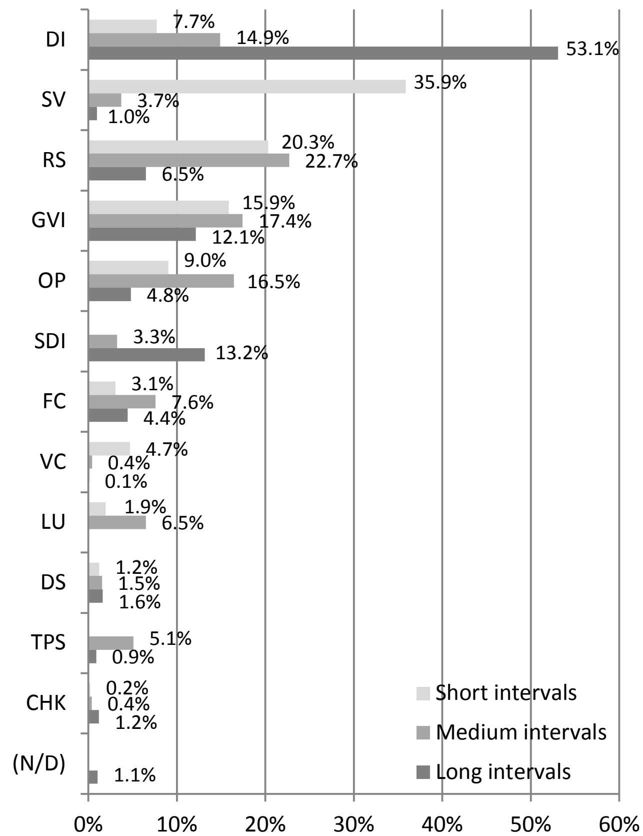


Figure 4. Distribution of man-hours over task codes in 12-year-period.

It is assumed that the 6- and 12-year heavy maintenance checks (former IL-/D-check) will persist as block check events. As a consequence, an interval extension of one task of a heavy maintenance check does not lead to an interval escalation of the total check, unless the intervals for all tasks of the checks are being extended accordingly.

Table 5. Equivalence maintenance program – Part 1 (equalized check events).

	TCG	Short interval		Medium interval	
		MH	Ratio	MH	Ratio
Routine	1	1,902	8.4 %	3,298	11.0 %
	2	2,454	10.8 %	2,355	7.9 %
	3	1,193	5.3 %	2,453	8.2 %
	4	8,881	39.2 %	3,773	12.6 %
Non-routine	5	3,588	15.9 %	8,250	27.5 %
	0	4,612	20.4 %	9,871	32.9 %
	Sum	**22,630**	**100 %**	**30,000**	**100 %**

Analysis of long interval tasks (6-/12-year check tasks and other tasks with intervals longer than generic C-check interval) show that about 89 % account for TCG 1 to 3,

which could be subject to task elimination. Only 9 % of the tasks account for TCG 4, which could be subject to interval escalation. The following analysis considers in connection with the block check events only the potential PHM impact of task redundancy, which accounts for almost 90 % of the routine work. The part 2 of the modeled equivalence maintenance program is summarized in Table 6.

Table 6. Equivalence maintenance program – Part 2 (remaining block check events).

	TCG	IL-Check		D-Check	
		MH	Ratio	MH	Ratio
Routine	1	941	89 %	1,568	89 %
	2	1,092		1,820	
	3	5,963		9,938	
	4	821	9 %	1,368	9 %
	other	183	2 %	305	2 %
	Sum	**9,000**	**100 %**	**15,000**	**100 %**
Non-routine	5	2,500	50 %	4,250	50 %
	0	2,500	50 %	4,250	50 %
	Sum	**5,000**	**100 %**	**8,500**	**100 %**

The applied generic modeling approach allows the comparison of a current maintenance program with any potential or future maintenance program without having described all maintenance tasks precisely. Particularly in early design stages of new aircraft, the proposed methodology could be beneficial in order to estimate the impact of alternative maintenance concept early on.

4.1.3. Unscheduled Maintenance

The modeling of unscheduled maintenance events in this study follows the approach as described in section 3.2.2. A total of 25 aircraft subsystems are considered in the study. The failure behavior of each subsystem is described by an individual non-parametric failure distribution function. It is assumed, that 12 of the 25 subsystems are potential candidates for a PHM implementation with a PHM coverage ranging from 0 to 100 percent. This means for the following analysis: A theoretical PHM-coverage of 100 % corresponds to a detection and prediction of all impending failures of the 12 selected subsystems. To limit the computing times, the PHM coverage rates for each of the 12 subsystems are assumed to be identical in all analyses.

4.1.4. Operational Boundary Conditions

In order to be able to evaluate the monetary results, a summary of the relevant economic data used in the analysis is given in Table 7. Assumed ticket prices for economy (EC) and business class (BC) influence airline revenues in the lifecycle CBA. The initial investment cost C_0 is assumed as 50 Mio. US$ (aircraft list price in 2008 less an assumed price discount of 35 %). This study should not provide cost estimates for the development and implementation of PHM systems. Rather, the goal is to derive maximum acceptable investment costs for PHM systems from the analysis results. Therefore, no additional fix costs for an airplane equipped with PHM are considered.

The delay costs of 0.63 US$ per passenger per minute include costs of passenger compensation and rebooking for missed connections, but also considers the costs of potential loss of revenue due to future loss of market share as a result of lack of punctuality (Eurocontrol, 2007). The internal rate of return r, which is used for the discounted cash-flow calculation, is assumed at 7 %.

Table 7. Summary of economic and operational data.

Parameter	**Unit**	**Fiscal year**	**Value**
Ticket price - EC	[US$]	2008	111
Ticket price - BC	[US$]	2008	334
Aircraft price C_0 (incl. 35% discount)	[Mio. US$]	2008	50
Labor rate (maintenance)	[US$/MH]	2009	70
Fuel price (fuel price scenario)	[US$/gal]	2013	2.49
Delay cost	[US$/min/pax]	2009	0.63
Average inflation	[1/year]		0.02
Discount rate r	[-]		0.07

4.2. Parameter Variation

Since the PHM and CBM concepts to be evaluated in this study are not implemented in commercial aircraft yet, actual performance characteristics of such concepts on aircraft level can hardly been estimated today. In addition, as mentioned previously, the proposed assessment methodology should provide assistance in the early design stage of future PHM and CBM concepts. For these reasons, it seems to be necessary to conduct a variation of parameters that characterize the performance of such concepts.

To limit the number of analyses and resulting calculation times in this study, three parameters are selected for the variation. These are “PHM coverage”, “task redundancy” and “interval escalation”. The parameters and their values are depicted in Table 8. The PHM coverage rate describes the portion of failures for which a specific prognostic system can report imminent failures, without consideration of false alarms and missed failures (see also section 4.1.3). The task redundancy rate is the percentage of preventive maintenance tasks that can potentially be eliminated if a PHM system is used to monitor the respective item (see also section 3.2.3). The interval escalation rate describes the factor by which preventive maintenance intervals may be extended if the corresponding item is monitored by a PHM system.

Table 8. Parameter space for analysis.

Parameter		Values
P_{Cov}	PHM coverage	0 0.25 0.5 0.75 1
P_{TR}	task redundancy	0 0.1 0.2 0.3........... 1
P_{IE}	interval escalation	0 0.25 0.5 0.75 1

The parameter space as defined in Table 8 results in 275 separate analyses, which have been conducted. In this study, each analysis consists of 100 simulation runs (Monte Carlo simulations) to account for the probabilistic behavior of the unscheduled maintenance module (due to the probabilistic modeling of the component failure behavior and the impact of PHM). Although a larger number of simulations might be desirable, the number had to be limited here to provide acceptable computing times.

4.3. Analysis Results

The performed analysis provides technical-operational and economic results. All results describe values for the operative lifecycle on a single aircraft. Since the study comprises 275 separate lifecycle analyses, only a limited selection of results can be presented in this paper.

Figure 5 and Figure 6 show the impacts of a variation of the parameters P_{TR} and P_{IE} on man-hours for maintenance tasks planned in AIRMAP. The absolute level of man-hours at $P_{Cov} = 1$ (Figure 6) is about 8,000 hours higher (over the lifecycle) than at $P_{Cov} = 0$ (Figure 5). The component maintenance events covered by PHM are responsible for this different level of man-hours. The shape of the curves is very similar in both cases.

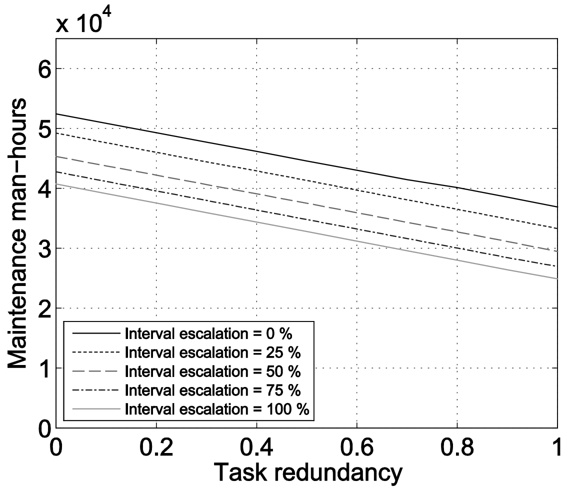


Figure 5. Man-hours for AIRMAP-tasks ($P_{Cov} = 0$).

As discussed in the beginning, a central goal of a PHM and CBM implementation is to improve the aircraft availability in order to increase the utilization. Both effects, the reduction of unscheduled events and the elimination of tasks, can contribute to higher aircraft utilization. Figure 7 shows that – even without a change in the aircraft operation concept – up to 420 additional flight cycles could be realized in aircraft lifecycle.

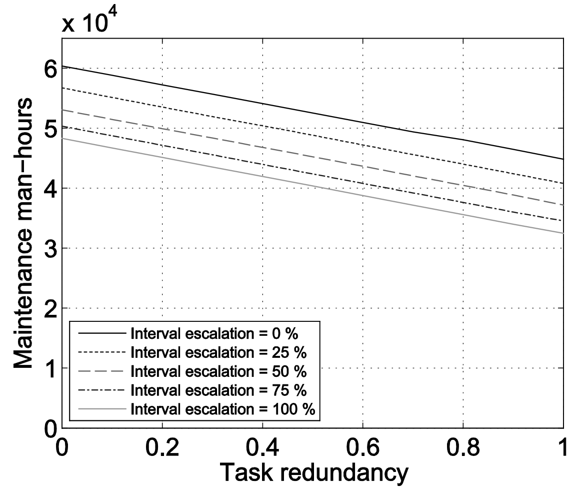


Figure 6. Man-hours for AIRMAP-tasks ($P_{Cov} = 1$).

Under the assumptions of this study, the avoidance of unscheduled events enables up to 260 additional flight cycles. Another 160 flights can be realized by shortening the maintenance downtimes for IL- and D-Checks in case of $P_{TR} = 1$.

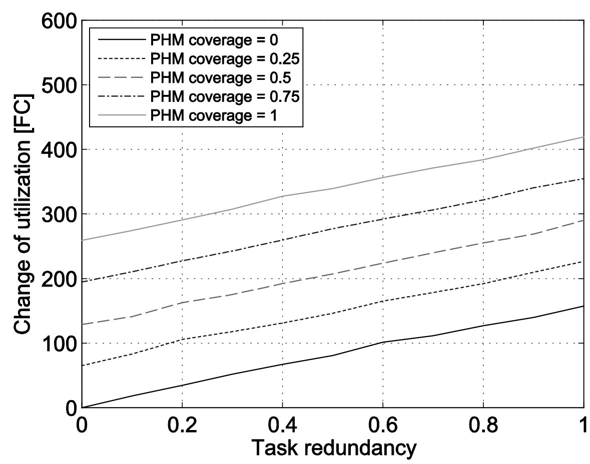


Figure 7. Aircraft utilization.

Figure 8 shows the impact of PHM coverage on the different categories of maintenance cost with the resulting changes of airline revenues and NPV. Since P_{TR} and P_{IE} are zero the figure shows the isolated benefit of the reduction of unscheduled events.

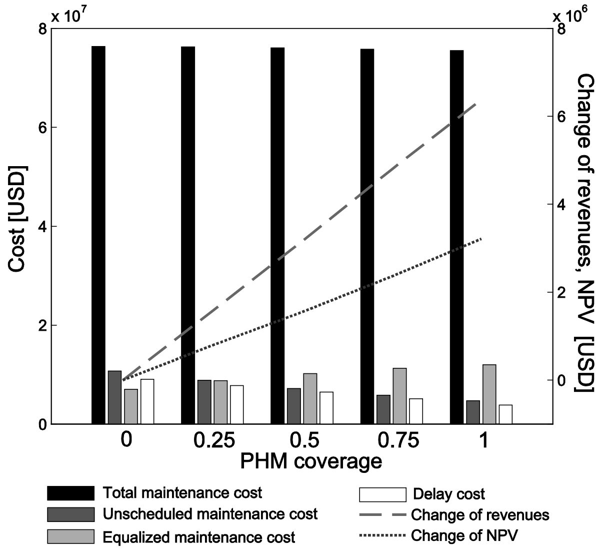


Figure 8. Impact of PHM on cost, revenues, and NPV (with $P_{TR} = 0$, $P_{IE} = 0$).

While total maintenance cost remains almost constant, a transition of unscheduled maintenance to dynamically planned, equalized maintenance (i.e. maintenance tasks planned in AIRMAP) can be observed for increases of PHM coverage. Moreover, the delay cost (which are not included in total maintenance cost) decreases significantly by almost 60 %. The reductions of unscheduled events lead to maximum increase of revenues of 6.3 million USD, which results in a higher NPV of 3.2 million USD (for $P_{Cov} = 0$).

The isolated influence of a variation of P_{TR} and P_{IE} on total maintenance cost is shown in Figure 9, when $P_{Cov} = 0$. The benefit of an escalation of task intervals can account for a cost reduction of 1.3 million USD ($P_{IE} = 1$).

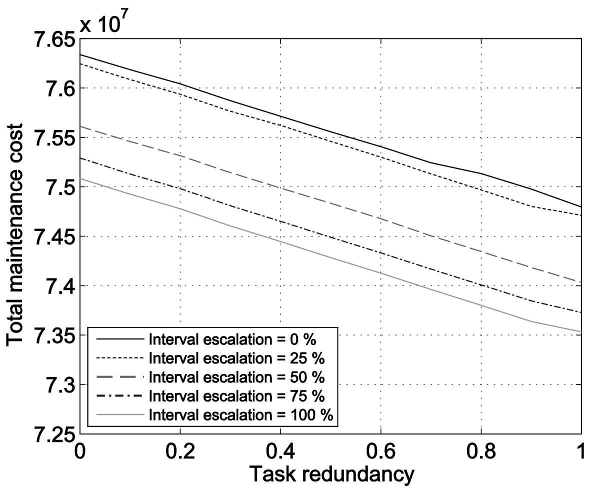


Figure 9. Total maintenance cost ($P_{Cov} = 0$).

Figure 10 shows the respective effect on total maintenance cost, when $P_{Cov} = 1$. It can be seen that the curves are principally shifted vertically to lower maintenance cost compared to Figure 9.

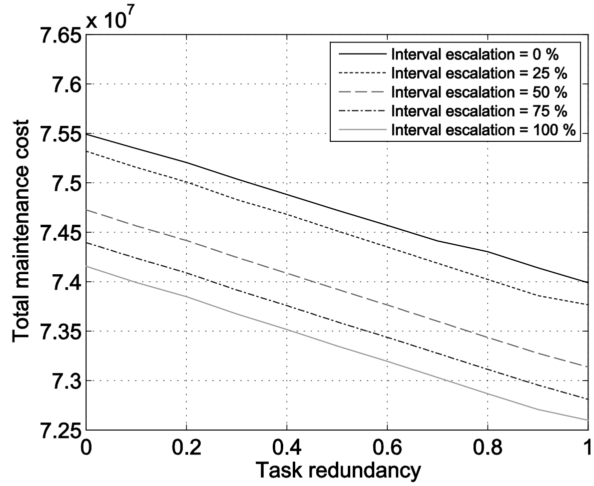
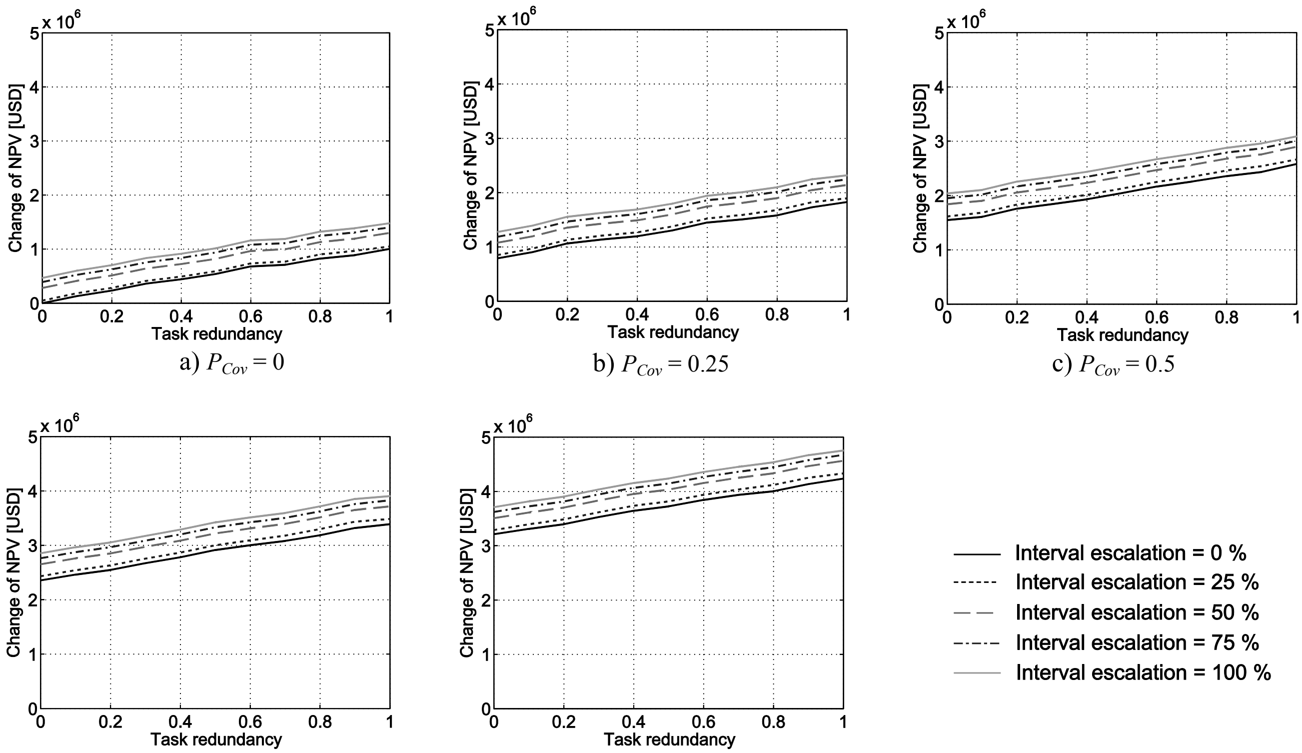


Figure 10. Total maintenance cost ($P_{Cov} = 1$).

Figure 11 describes the highest aggregated economic results of the presented study. The monetary benefit of an aircraft operator, expressed as NPV, is shown for all variations of P_{Cov}, P_{TR}, and P_{IE}. Each of the five parts of Figure 11 shows the impacts of the task redundancy rate and the interval escalation factor on airline NPV with the respective PHM coverage rate. It can be seen that the maximum benefit of an interval escalation (i.e. the difference of NPV for P_{IE} =0 % and P_{IE} =100 % in each subfigure) accounts for around 0.5 million USD. The maximum overall increase of NPV that could be realized under given assumptions is 4.75 million USD (as depicted in Figure 11 e). Although it is unlikely that a PHM-coverage of 100 % for the selected systems could be achieved at an acceptable price, the results show the range of potential benefits. The increase in NPV by a certain PHM/CBM configuration is at the same time the upper limit of the acquisition cost of such a system, which could be accepted.



a) $P_{Cov} = 0$ b) $P_{Cov} = 0.25$ c) $P_{Cov} = 0.5$

d) $P_{Cov} = 0.75$ e) $P_{Cov} = 1$

Figure 11. Impact of PHM coverage, task redundancy, and interval escalation rates on NPV.

The results presented in this section are on single aircraft level. The analysis does not consider interdependencies between different aircraft in a fleet. While AIRMAP is able to conduct the maintenance planning optimization for a fleet of aircraft, the other modules of AIRTOBS can only handle single aircraft at present.

5. CONCLUSION AND OUTLOOK

In this paper we have presented an integrated approach to model the impacts of PHM and CBM planning from an aircraft lifecycle perspective. The integration of the CBM planning approach in a lifecycle cost-benefit model allows the economic assessment of a PHM and CBM implementation in future aircraft. The application of the assessment approach can deliver valuable requirements for the future development of PHM and CBM concepts and demonstrate its consequences for operators and MROs.

At present, the assessment approach is limited to a single aircraft analysis. An extension of AIRTOBS on a fleet-level basis would allow using the complete functional range of AIRMAP, i.e. scheduling maintenance tasks and planning capacities for a fleet of different aircraft types on an airline's network. It is expected that an analysis on a fleet-level will result into a lower economic benefit per aircraft. This is because several aircraft compete for limited maintenance resources, leading to less efficient solutions of the CBM planning process.

In further studies we intend to analyze the effects of varying daily aircraft utilizations in order to investigate the applicability and benefits of the approach for different airline business models (e.g. network or low-cost carrier). Low-cost carriers usually have significantly higher aircraft utilizations and therefore shorter and less maintenance opportunities compared to a network carrier operating a similar route network. This fact may imply a higher sensitivity to flight schedule disturbances and consequently also a greater benefit from the reduction of unscheduled events due to the use of PHM. In contrast, decreasing aircraft ground times make it more difficult to solve the CBM planning problem and potentially reduce the efficiency of the maintenance plan.

Further improvements of the optimization algorithm included in AIRMAP in terms of computation times would allow analyzing significantly larger parameter spaces and a higher number of Monte Carlo simulations in the future.

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NOMENCLATURE

AD	Airworthiness Directive
AIRTOBS	Aircraft Technology and Operations Benchmark System
ATA	Air Transport Association
BC	business class
CBA	cost-benefit analysis
CBM	condition-based maintenance
DOC	direct operating cost
EC	economy class
FC	flight cycle
FH	flight hour
FSB	Flight Schedule Builder
LC2B	Life Cycle Cost-benefit Model
LCC	life cycle cost
LRU	line replaceable unit
MEL	minimum equipment list
MH	man-hours
MRO	maintenance, repair, and overhaul
MSB	Maintenance Schedule Builder
MTTR	mean time to repair
MTBUR	mean time between unscheduled removals
NFF	no fault found
NP	non-deterministic polynomial-time
NPV	net present value
PHM	Prognostics and Health Management
ROI	return on investment
RUL	remaining useful life
TCG	task code group
SB	Service Bulletin
XML	Extensible Markup Language

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